

**NASA TECHNICAL
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NASA TM X-71538

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(NASA-TM-X-71538) CLEAN FUELS FROM
BIOMASS (NASA) CSCL 20M

N74-19706

63/03 Unclass
34370

CLEAN FUELS FROM BIOMASS

by Y. Y. Hsu
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER proposed for presentation at
the 10th Southeastern Seminar on Thermal Science
New Orleans, Louisiana, April 11-12, 1974

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CLEAN FUELS FROM BIOMASS

Yih-yun Hsu

INTRODUCTION

About two years ago, a NSF-NASA panel was formed to examine the feasibility of various means of utilizing solar energy. Many well-known means of using solar energy were examined, such as solar house heating and cooling, wind power, solar power plant etc. One area that is relatively little known to the public is that of converting biomass to portable fuels. But presently, both NSF and NASA are conducting studies in this area. The study conducted at NASA Lewis Research Center is the topic of my talk today. The basic concept of obtaining fuels from solar energy is very simple. (Fig. 1) Plants synthesize biomass from H_2O and CO_2 with the help of solar energy. If the biomass were buried underground for millions of years, it would perhaps be converted to fossil fuels. However, if we want to convert biomass to fuel with a more practical time limit, we must develop other conversion methods. There are three methods we can use. One is pyrolysis, which breaks the cellulose molecules into smaller molecules under high temperature in the absence of oxygen. The second method is anaerobic fermentation through which the biomass is converted to methane by bacteria. The third method is hydrogenation which converts biomass into artificial petroleum. The third method is rather expensive at the present time, so we will only talk about pyrolysis and fermentation processes.

In order to make the fuels produced from our conversion scheme competitive with other energy sources, it is necessary to keep the cost down. Cost-reduction can be realized only if we analyze the whole system carefully to pin point the crucial areas where savings can be achieved. Furthermore, total system study is needed to determine the energy budget, the environmental impact and the

social-economical impact. At present, we are only working on the cost reduction part of analysis. We will study the other impacts only if conversion of fuel from biomass looks economically feasible.

In this talk, I am going to touch on three subjects. (1) Does the U.S. have the resources to provide fuels from agricultural products? (2) What is the status of the conversion technology? (3) A system study.

RESOURCES

Biomass can be defined as the organic material originally formed by nature through photosynthesis. Biomass is available not only from agricultural crops but from other sources, such as algae, trees, agriculture residue, agricultural waste and urban waste. In fact, urban waste is the most readily available and most economical source of biomass. Each person in the U.S. produces about one ton of waste a year, of which about 50% is made of degradable organics. Agricultural waste and agricultural residue are also available in large quantity. But if we want to make biomass fuel a significant source of energy, additional material has to be grown for that purpose. The crops grown as raw material for fuels can come from farms, forests, and from water. The major portion perhaps still has to come from farm crops, since the land farming technology is highly developed. Thus, while we do not rule out silvaculture and aquaculture, today's talk will focuss on land farming.

To develop a farm crop with the purpose of harvesting it for fuel conversion, it is important to find which plants have highest growth yield. The yield is a function of both the solar energy input and the photosynthesis efficiency of plant species. As shown in figure 2, (ref. 1) the solar energy input varies from 200 to 300 watts/m² depending upon the latitude of the region. The photosynthetic efficiency of the plant depends upon the complexity of the organic products. It takes more solar energy to form one gram of seed, than that required for one gram of

vegetable oil, which in turn is more than that for cellulose. Thus, as shown in fig. 2 (Ref. 1), the photosynthetic efficiency for corn (considered as seed plant) is less than 1% while efficiency for Napier grass is almost 2%. Some very promising candidates can be found in Table 1 (Ref. 2). However, for the great plains of the U.S., at the present time we probably can only assume to have 10 tons/year-acre of yield; as represented by corn in Table 1. This yield of 10 ton/year-acre will be used as a reference basis in our analysis.

Having the yield figure available, we need the land area that can be used for fuel crop. This land should not be taken from present crop farm land. Table 2 shows land areas in the U.S. in various types of usage (Ref. 3). About 1 billion acres are farm land and about 700 million acres are not. If we lump all the land that is not currently used for farming, we find that about 1 billion acres of land are available. If we assume only 15% of this available unused land could produce a crop averaging 10 tons/acre, we would have 1500 million tons of biomass per year. Assuming an equivalent fuel yield of two barrels of combustible oil per ton of biomass (Ref. 6), we would have about three billion barrels of combustible oil a year. This is equivalent to 1/5 of today's energy used in the U.S.

Thus, we can say that if fuel crop farming is carried out in large scale, a significant portion of the nation's fuel energy needs could be met.

CONVERSION PROCESS

As mentioned previously, both pyrolysis and fermentation processes can convert biomass into fuel liquids or gas. Each process represents an old technology. The problem is to build large-scale conversion plants to turn out products at competitive cost. Since these processes have been in existence for many years, there is no need to go into detail here except to give a general discussion and to enumerate some possible problems involved for large scale operation.

Pyrolysis

When the cellulose is heated to high temperature, it decomposes into small molecules. It was believed (ref. 4) that cellulose polymers first decompose into levoglucosan molecules which in turn break into smaller molecules, as shown in Fig. 3. The combustion of cellulose really involves the two steps, i. e., the pyrolysis of cellulose and oxidation of the pyrolysis products. If cellulose is heated in the absence of oxygen, only pyrolysis takes place. The distillation of "wood alcohol" and the production of wood charcoal are examples of pyrolysis processes. The products of pyrolysis include char, gasses (CH_4 , CO , CO_2 , etc.), and liquids (tar, oil, acids, acetones, alcohols etc.). The composition of the product depends upon the temperature and the rate the feed is brought up to that temperature. In general, under higher temperature, more gasses are formed. A faster heating rate gives a more uniform product. Thus in pyrolysis, the heating unit is very important.

The heating units for pyrolysis can be of batch type, or continuous type such as conveyer belt, or fluidized beds. Fluidized beds are more suitable for large scale operation due to the efficient heat transfer process in the bed. The bed can be heated by combusting char and some feed in the lower half of the bed, or the bed particulates (such as sand) can be heated in a neighboring combusting fluidized bed and then transferred back to the pyrolysing bed while the bed particulates are still hot. A typical two-bed system is shown in Fig. 4. A recent pyrolysis process that won considerable attention is the Garrett process which is supposed to involve flashing pyrolysis (Ref. 6); however, details of the heating method has not been made public yet.

Typical compositions of pyrolysis products are shown in Table 3 and 4b (Refs. 5 and 6). As can be seen, the compositions can vary considerably, depending upon process and condition. Since the pyrolysis is an endothermic reaction, heat must be supplied. Usually, the heat is supplied by combusting some of the products,

such as char or gas. Roughly, only about 50% of the heating value of the feed is recovered as energy in the fuel. Thus, for a ton of feed, one can recover about 2 barrels of oil, or about 10 million Btu of heating value.

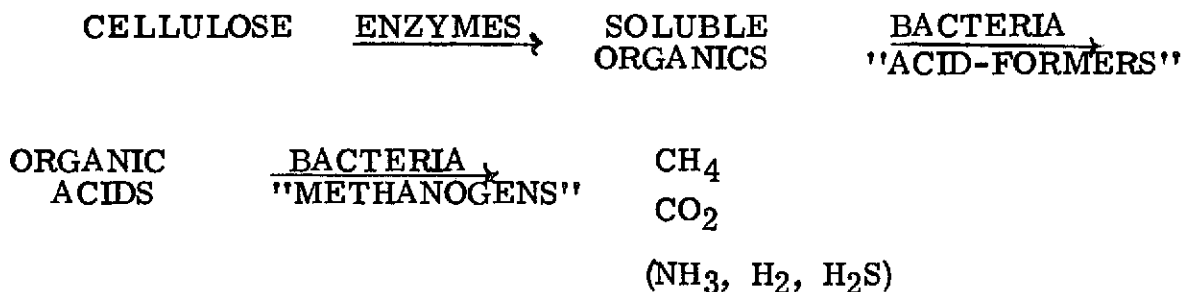
There are some areas where research and development should be carried out before large scale pyrolysis plants are built. The proper cascade utilization of heat is important for energy conservation. The scaling-up of the fluidized bed is another important problem. Other items include the optimization in feed size reduction and drying of feed and the efficient recovery of products.

Fermentation

When cellulose is subjected to anaerobic fermentation at about 80-90°F methane is formed. The reaction can be written as



It is generally believed that the process undergoes the following steps.



The first two steps are comparatively rapid, the rate controlling reaction being the methane-generation step. The anaerobic fermentation reaction is a naturally occurring process, maintained with relative ease as long as the temperature is steady and the pH is maintained in the proper range (6.5 - 7.5). No preparatory sterilization is required and the microorganisms that carry out the reaction are naturally produced. The only equipment needed for methane generation is a closed digester tank. Hydraulic residence times of about

10 days are considered necessary for steady state methane production. Typical process diagram is shown in Fig. 5.

Because the fermentation process is simple and easy to carry out, it has been used for many years in many places. For example, in 1897, anaerobic fermentation of cows waste was used to generate electricity in Bombay. And today in Taiwan, the farmers are using this process to generate methane from pig waste (Fig. 6, Ref. 7). About 10 pigs can supply enough methane for the cooking needs of a household. And in the U.S., many sewage treatment plants are generating methane from sewer sludge. For one ton of feed, about 1000 cu ft. of methane can be generated, with a heating value of about 10 million Btu.

However, the methane generation process can be stopped if the pH value is not right. For a large plant, it would become a big disposal problem if a large tankful of slurry just turned sour. Another problem is that people still do not understand the basic mechanism well enough. The whole process is still an art. Thus optimization is even more difficult. Furthermore, due to the long residence time, a large digester volume per unit weight of feed is required. For a large plant, the total volume of the digesters can be considerable and the cost of handling large amounts of fluids and sludge can be a sizeable fraction of the conversion cost.

SYSTEM ANALYSIS FOR FUEL FROM CROPS

A rough cost estimate for conversion of crops to fuel is shown in Table 5 (Ref. 8). If we consider the whole process, starting from the growing of crops in the field, and ending at the exit of the conversion plant, we can see that many operations are involved, including farming, harvesting, purchasing, collection transportation, storage, and finally conversion (Fig. 7). Cost optimization can be achieved by minimizing the expenses or maximizing the yield in each step. Thus we will try to analyze each step from the point of view of the manager of the conversion plant. (Ref. 9). As

was noted in Table 5, the cost of the crop is the most important item in the fuel cost. However, the efficiency of farming is beyond the control of the manager of the conversion plant. He can only hope that through some research effort in agronomy and agricultural engineering, the cost of crop production can be reduced. However, the determination of purchase price for the crop is a game between the plant manager and the farmer. Before he can post an offering price, the plant manager must have some idea as to the availability of the crop and the cost for the farmer to produce it.

Purchasing Policy for the Plant Manager

In order to understand the supply picture, the plant manager can run a computer simulation to determine the statistical distribution of the cost for the farmers to grow a certain crop. An example of this is a computer simulation run for the hypothetical case of growing Kenaf in Ohio. Kenaf is a high yield cellulose plant grown in Florida. It is a fast-growing, pest resistant plant (Ref. 10). It was grown in the experimental stations in Ohio and has a yield about three times that of hay. To make an estimate of the probable cost of growing Kenaf in Ohio, we use the statistical data of the cost of growing and harvesting hay. Basically, the yield is a function of geographical location and soil conditions, and the cost is a combination of land charge, labor and machine cost. The labor cost, in turn, is a function of a farm size (Ref. 11-17). We assume we have 1000 samples of 100 acres each. These 1000 samples will statistically reflect the geographical distribution, soil distribution, and size distribution of the whole state. By properly assigning the cost and yield factors to these samples, we can arrive at a cost profile for growing hay as well as for growing Kenaf. The profile for growing Kenaf is shown in Fig. 8. From this figure, one can determine what percentage of the total crop can be purchased at a given offering price, if the farmer is expected to

realize a net profit of \$20/acre of net profit. For example, at \$6/ton, only 4% of crop can be bought with \$20/acre profit for the farmer, at \$9/ton, 39% can be bought, while at \$12/ton, 66% can be bought. From this figure, we can say that the elasticity is at $\alpha = \ln \left(\frac{0.66}{0.39} / \frac{12}{9} \right) = 0.24$. A manager equipped with such information would be able to offer a price to acquire just enough raw material for his plant. Too high a price will result in surplus and too low will result in shortage. Of course, the problem can be much more complicated if there are more than one plant competing for a limited supply, or if the farmers formed an embargo.

Collection and Transportation

After the crop is purchased, the farmers will deliver the crop. The crop can all be delivered directly to the conversion plant, or to some collecting station. Direct delivery will save handling cost but trucking may not be cheapest means of transportation. The use of intermediate collection stations may incur additional handling charges but the crops might then be shipped to the plant through some cheaper means of transportation, such as by train. The optimal distribution of a collection network can be shown to be a function of the costs of different modes of transportation, the handling charge, and the capacity of the plant.

$$\text{Collection Cost, } C_2 = \frac{C_{op}}{WL^2} + \frac{C_{truck} L}{2} + \frac{C_{train} M}{2} \quad \text{Eq. 1}$$

Where L & M are the width of the square territories for the collection station and for the conversion plant respectively. W is the yield per unit area. It is intuitively clear that if there are two plants, it is more economical for each to draw material from its own territory than to share a territory twice the size.

Inventory

The crops are usually seasonal. Thus, during winter, unless some special crop can be grown to keep a steady supply of raw material, the conversion plant will have to draw from the inventory stock. In Fig. 9, the supply from various crops A, B, C, are shown as two crops, one large crop, or three small crops. The combined supply curve is shown in Fig. 10 together with the demand curve. As the winter wears on, the stock is depleted. The demand still exceeds the combined supply of various crops even in the spring. The supply finally surpasses demand in the summer. At that time, the inventory reaches its lowest point and from then on the stock builds up until it reaches maximum at the end of large harvest. But to maintain a large stock during the winter season requires a large warehouse which would then only be fully used for a few months. To save cost, it may be worthwhile to pay a higher price in winter for some special crop, such as low grade wood from tree farms. Or, it may pay to subsidize farmers to store some stock for winter delivery. During the spring, the supply can be enhanced if a better price is offered, while in fall the purchase price can be lowered since the supply is abundant. Thus, the inventory operation and the purchasing operation are really closely related, and the elasticity factors mentioned in the section on purchasing operation is an important factor for inventory decision.

$$\text{Total Cost} = \int_0^T \sum_{i=1}^n (C_{i1} + C_{i2}) f_i dt + nC_3 + C_4' I_0 + \int_0^T C_5 I dt \quad \text{Eq. 2}$$

The strategy is a proper trade-off between purchasing cost and the storage cost. The ultimate goal is the optimization of cost.

Optimization in the Conversion Plant

There are many optimization possibilities existing in a processing plant. Most of those involve standard good engineering practice. However, there is one area of optimization which has

usually been neglected, that is the cascade utilization of energy. In the past, when energy was cheap, the savings through waste heat utilization did not warrant the extra equipment cost. As the energy cost rises, optimal utilization of energy becomes a more important consideration. For example, in the pyrolysis plant (see Fig. 11) the heat generated by the combustor at 1000°F is used in the reactor to supply the heat for pyrolysis. The effluent from the reactor can be cooled by coolant which, in turn, can be used to supply heat at 400°F for drying purposes. The waste heat from the drier can be further utilized for plant heating.

OTHER CONSIDERATIONS IN TOTAL SYSTEM ANALYSIS

In the last section, focus was mainly on cost optimization and energy utilization. There are other considerations which should be included in a broader scope, total system study.

Recycling of Material

The sludge from the fermentation plant or the ash from the pyrolysis plant contains most of the mineral material that the biomass extracted from the ground. These minerals can be recycled back to the ground. The only major item that needs replenishment is nitrogen, and manufacturing of nitrogen needs energy. Hydrogen and carbon are recycled through the atmosphere. In a total system analysis, the material balance should be properly considered if the whole operation is to be sustained indefinitely.

Other Environmental Impacts Considerations

If the fuel crop economy is going to be a sizable fraction of the U.S. economy the environmental impacts of the conversion plants, the effects of not plowing the agriculture residue back into the land, especially its effects on soil and subterranean community; and the social-economical impact of a new line of industry should all be considered. If one wants to broaden his scope further, one could even re-examine the urban structure and the interaction between industrial areas, rural areas, and peoples living areas.

CONCLUSION

In this discussion, I have examined the potential of growing crops as a source of fuels. It can be concluded that in the U.S. enough unused arable land is available so that even with a modest rate of crop yield, a significant fraction of the energy needs of the nation could be supplied by fuel crops. The technologies for fuel conversion are available; however, some research and development efforts are needed for scaling-up design. The present cost of energy obtained from fuel crops is about \$2-3/million Btu which is still high in comparison with other sources, such as natural gas (\$1.5/million Btu.). But with proper management through careful system analysis, the cost can be reduced. Furthermore, it is important that a total system analysis be made to consider interactions of various operations and various sub-systems.

A final estimate of interest for this discussion concerns the capability of the U.S. to sustain her population through agriculture and land if all the other energy sources were unavailable. Table 6 is based on figures deduced from various sources (ref. 3, 18, and 19). It shows the land area per capita needed to sustain a living standard at 1970 level. The last figure indicates that the U.S. could support 250 million people in that fashion.

Acknowledgement

The contents of this report are drawn from studies made by the Clean-fuel team in the Fluid Physics and Chemistry Branch of the Lewis Research Center, formerly under the leadership of Warren Rayle. Much information was supplied by other members of the team, R.W. Graham and Thaine Reynolds. Assistance and advice provided by the Ohio Agricultural R/D Center of Wooster, Ohio are deeply appreciated.

NOMENC LATURE

C_1	Purchase cost \$/ton
C_2	Shipping cost \$/ton
C_3	Set-up cost for each crop \$
C_4	Capital investment cost for warehouse of size I_0 \$/ton
C_5	Storage cost \$/ton-year
C_{op}	Operation cost of collection station \$
C_{train}	Freight for train \$/ton-mile
C_{truck}	Freight for truck \$/ton-mile
f_i	Supply rate of i^{th} crop
I	Inventory, ton
I_0	Max. inventory
L	Length or width of the territory of a collection station
M	Length or width of the territory of a conversion plant
W	Yield of crop, tons/sq. miles
α	supply elasticity, $= \frac{df}{f} / \frac{dC_1}{C_1}$

Subscripts

i	i^{th} crop
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TABLE I. - REPRESENTATIVE YIELD VALUES OF DRY
MASS FROM OARDC SURVEY

TONS/ACRE/YR		
CROP	LOCATION	YIELD
NAPIER GRASS	PUERTO RICO	21.6
NAPIER GRASS	INDIA	15.5
CONGO GRASS	PUERTO RICO	22.4
BUFFELGRASS	-----	28
DALLIS GRASS	TAIWAN	10.7
KIKUYU GRASS	TAIWAN	23.3
CANARY GRASS	U. S. & CANADA	3.6 TO 8.3
RYEGRASS	GT BRITAIN	10
SUGARCANE	U. S.	9.5 TO 10.7
CORN	U. S.	10
SUGARBEETS	U. S.	9.5

CS-69421

TABLE II. - SUMMARY OF LAND USE IN USA
SOURCE, U. S. DEPTS OF AGRICULTURE & COMMERCE (1964 DATA)

	MILLIONS OF ACRES
<u>FARMLAND</u>	
CROPLAND	335
IDLE CROPLAND	52
CROPLAND USED FOR PASTURE	57
PASTURE GRASSLAND	490
FOREST & WOODLAND	146
FARMSTEADS & OTHER LAND	30
	<u>1110</u>
<u>LAND NOT IN FARMS</u>	
GRAZING LAND	293
FOREST LAND	443
	<u>736</u>
<u>TOTAL LAND</u>	1846
<u>AVAILABLE LAND WHICH COULD BE USED IN AGRICULTURE</u>	
IDLE CROPLAND	52
CROPLAND FOR PASTURE	57
LAND NOT IN FARMS	736
FARM FOREST & WOODLAND	146
	<u>991</u>

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TABLE III. - TYPICAL YIELD FOR
PYROLYSIS PROCESS
GARRET PROCESS (REF. 6)
(T = 950° F)

HEAT VALUE	
CHAR 18%	11 500 BTU/LB
OIL 48%	12 600 BTU/LB
GAS 26%	550 BTU/FT ³
EFF	50%
RECOVERS	10 MMBTU/TON DRY FEED

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TABLE IV. - TYPICAL ANALYSES OF RAW MATERIAL AND PRODUCTS IN
PYROLYSIS PROCESS (REF. 5).

(a) ANALYSIS OF SOME DRIED AGRICULTURAL WASTES

WASTE	PINE BARK	BOYINE WASTE	RICE STRAW	CELLU- LOSE
ULTIMATE ANALYSIS, WT PCT				
C	52.3	42.7	39.2	44.4
H	5.8	5.5	5.1	6.2
O	38.8	31.3	35.8	49.4
N	0.2	2.4	0.6	0
S	0	0.3	0.1	0
MOISTURE, WT PCT	4.9	3.6	7.4	0
ASH, WT PCT	2.9	17.8	19.2	0
HEATING VALUE, BTU/LB	8780	7380	6560	7520

(b) PRODUCTS OF PYROLYSIS

WASTE	COW MANURE	RICE STRAW	PINE BARK
TEMPERATURE, °C	500-900	200-700	900
YIELDS PER TONS OF WEIGHT			
GAS, CU FT	10 983	5981	20 154
OIL, GAL	17.4	11.0	5.5
AMMONIUM SULFATE, LB	48.2	7.3	8.8
AQUEOUS, GAL	36.4	60.3	29.4
RESIDUE, LB	702	800	630

TABLE V. - ESTIMATES OF CONVERSION TO FUEL COSTS

ASSUME CONVERSION EFF = 0.5

FEEDSTOCK	PER TON	\$10.00	\$15.00	\$20.00	\$25.00
COST	PER MILL BTU	.67	1.00	1.33	1.67
1. PYROLYSIS PLANT (FROM GRAPH INITIAL COST IS \$600/MILL BTU/DAY INPUT FOR A 1000 TON/DAY CAPACITY) ASSUME 20-YR LIFE THEN COST/MILLION BTU OUTPUT		.10	.10	.10	.10
2. MAINTENANCE (EPA MANUAL STIPULATES 1 TO 2% OF INITIAL COST) COST/MILLION BTU OUTPUT		.04	.04	.04	.04
3. TRANSPORTATION (50 MILES OF HAULING)		.20	.20	.20	.20
4. OPERATION (NEGLECTIBLE FOR HEAT EXCHANGER EQUIPMENT)		-----	-----	-----	-----
5. TAXES & INSURANCE (2% OF AVG COST OF PLANT)		.04	.04	.04	-----
TOTAL COST/MILL BTU INPUT		\$1.05	\$1.38	\$1.71	\$2.05
TOTAL COST/MILL BTU OUTPUT		\$2.10	\$2.76	\$3.42	\$4.10

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TABLE VI. - ABILITY FOR U.S. TO SUPPORT HER

POPULATION BY AGRICULTURE AND LAND

TOTAL ENERGY NEED OF U.S. = 3.5×10^8 BTU/PERSON IN 1970ENERGY SUPPLIED BY FUEL CROP AT 10 T/ACRE-YR = 10^8 BTU/ACRE

LAND REQUIRED FOR ENERGY 3.5 ACRES/PERSON

LAND REQUIRED FOR FOOD 1.5 ACRES/PERSON

LAND REQUIRED FOR SUPPLIES 1 ACRES/PERSON

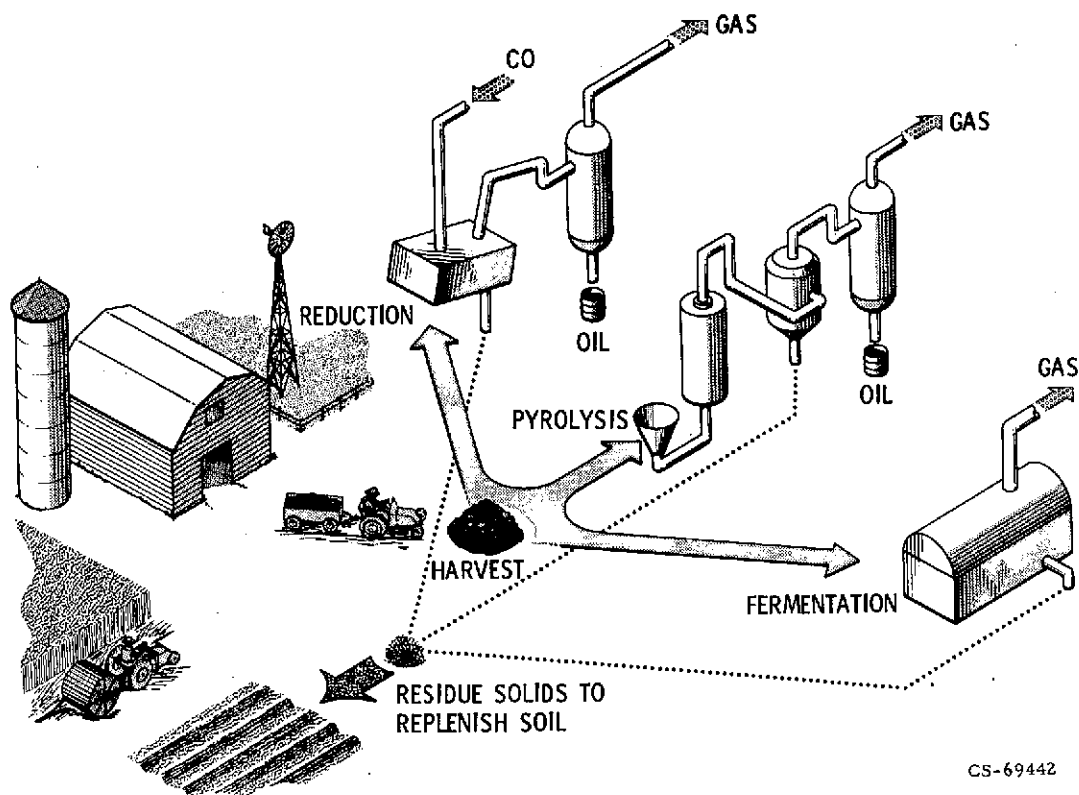
LAND REQUIRED FOR LIVING SPACE 0.5 ACRES/PERSON

TOTAL 6.5 ACRES/PERSON

TOTAL ARABLE LAND = 18×10^8 ACRES

TOTAL POPULATION THAT CAN BE SUPPORTED = 250 MILLION PERSONS

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Figure 1. - Methods of converting crops to fuel.

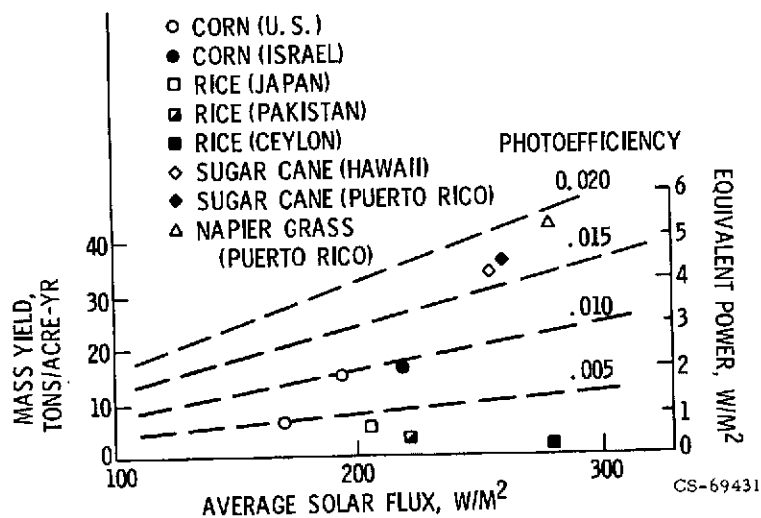
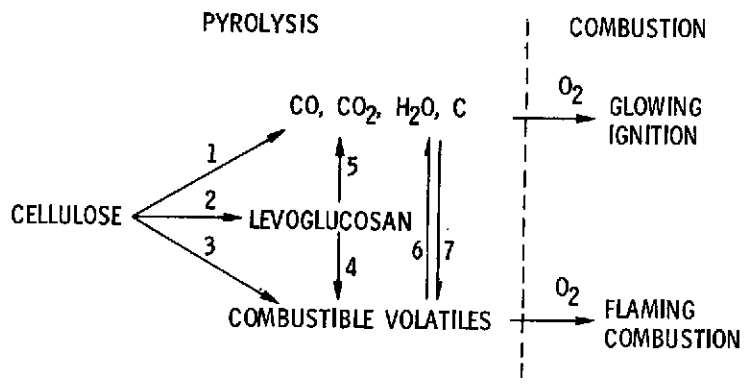


Figure 2. - Biomass yield from photosynthesis.



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Figure 3. - General reactions involved in pyrolysis and combustion of cellulose.

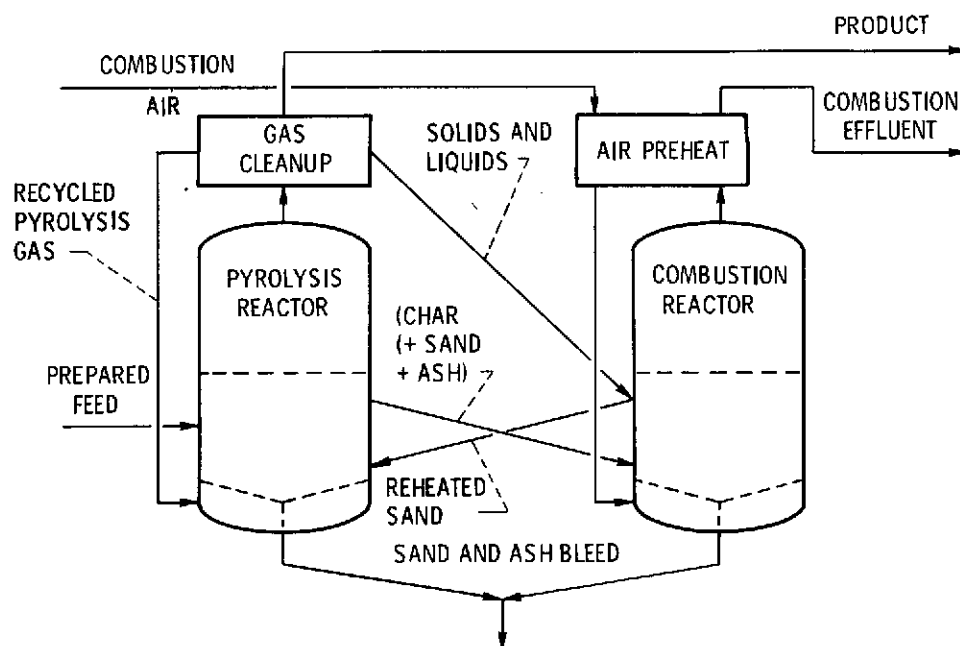


Figure 4. - Typical two-bed fluidized bed system for pyrolysis.

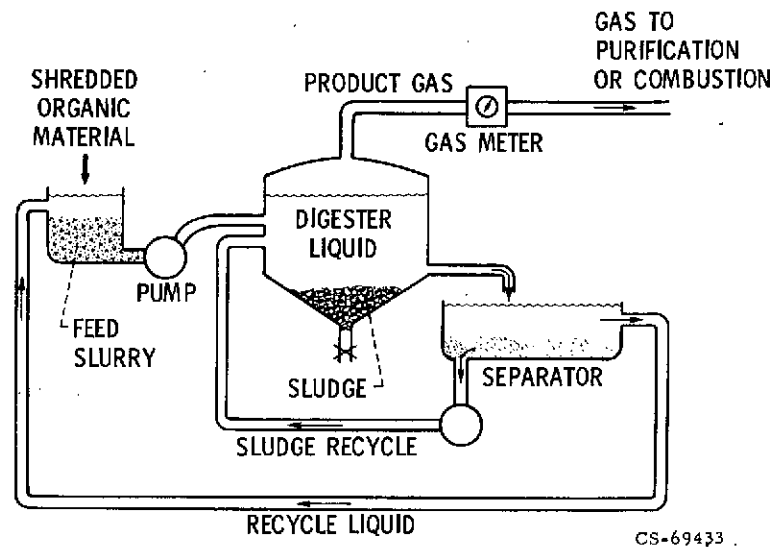


Figure 5. - Typical fermentation system for production of methane.

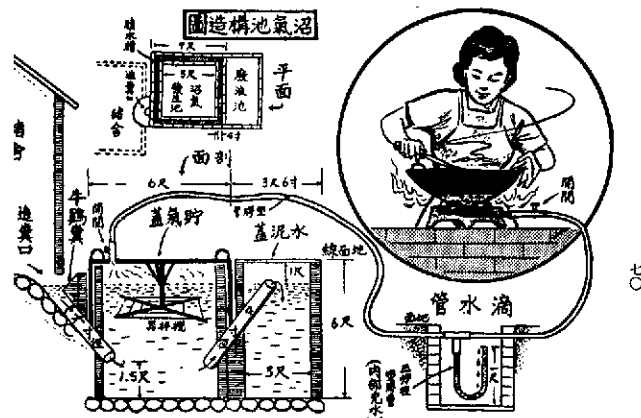


Figure 6. - Small-scale methane generator used by farmers in Taiwan (ref. 7).

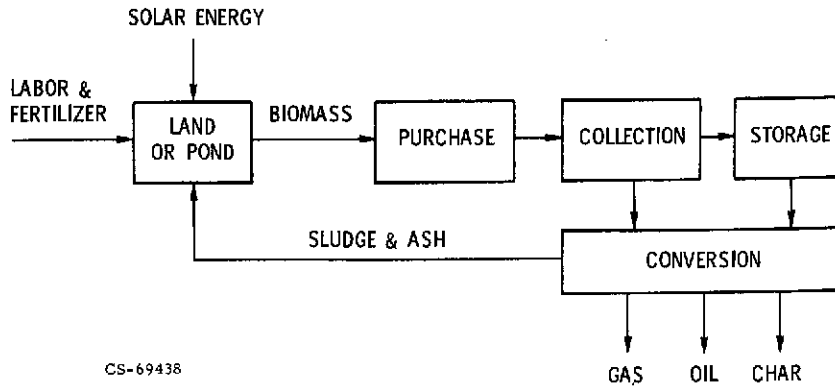


Figure 7. - A diagram showing the overall system for conversion of biomass.

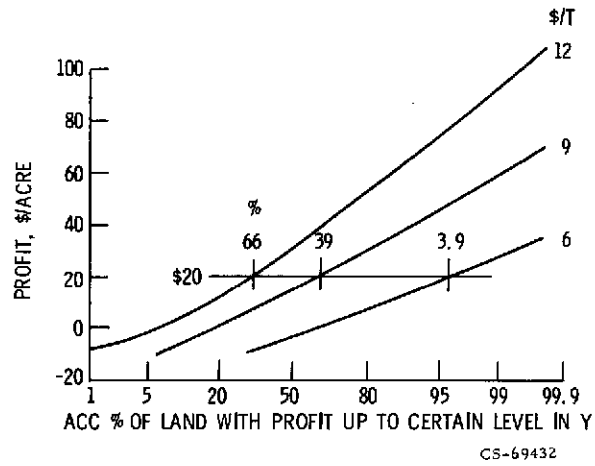


Figure 8. - Profit profile for Kenaf as crop with purchasing price as parameter.

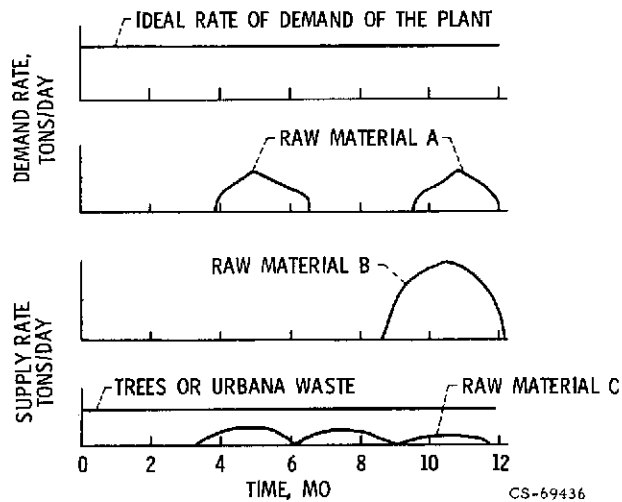


Figure 9. - Crop distribution over the span of a year.

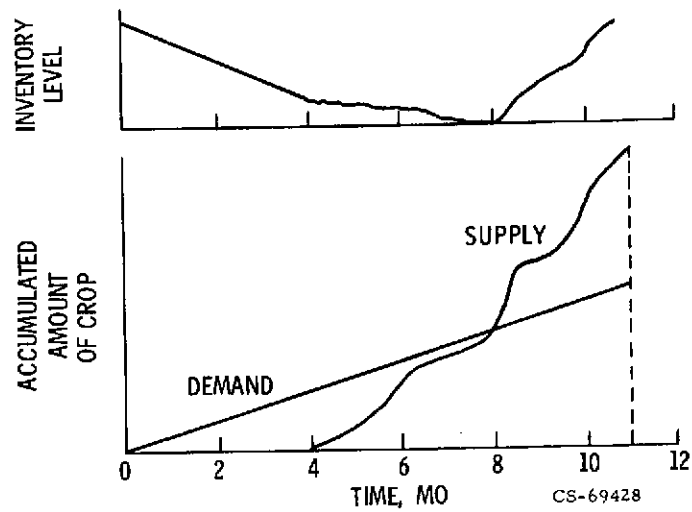


Figure 10. - Demand and supply of raw material for fuel conversion.

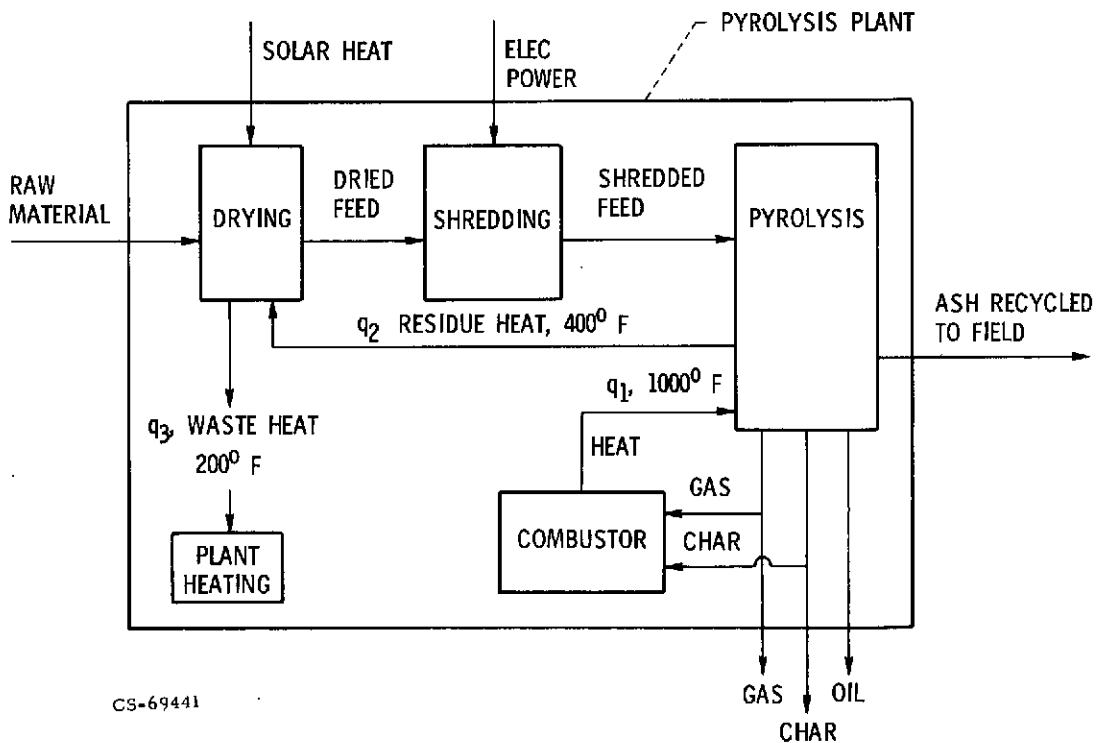


Figure 11. - Energy utilization in a pyrolysis plant.